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Heat Transfer Augmentation of Air Cooled Internal Combustion Engine Using Fins through Numerical Techniques

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Abstract

Fins are basically mechanical structures which are used to cool various structures via the process of convection. Most part of their design is basically limited by the design of the system. But still certain parameters and geometry could be modified to better heat transfer. In most of the cases simple fin geometry is preferred such as rectangular fins and circular fins. Many experimental works has been done to improve the heat release of the internal combustion engine cylinder and fin efficiency. A numerical investigation has been carried for a finned metal cylinder using CFD and is validated against the experiments carried out. A transient numerical analysis is carried out with wall cylinder temperature of 423 K initially and the heat release from the cylinder is analyzed for zero wind velocity. The heat release from the cylinder which is calculated numerically is validated with the experimental results. In the present paper an effort is made to study the effect of fin parameters on fin array performance which includes variation in pitch and fin material. In addition, the current paper considers the effect of air flow velocity on different fin pitch. With the help of the available numerical results, the design of the internal combustion engine cooling fins can be altered for better efficiency.

Keywords: Heat transfer, extended surfaces, rectangular fins, grid generation, engine block.

Introduction

An air cooled motorbike engine dissipates waste heat from the cylinder through the cooling fins to the cooling air flow created by the relative motion of moving motorbikes. The cooling system is an important engine subsystem. The air cooling mechanism of the engine is mostly dependent on the fin design of the cylinder head and block. It also depends on the velocity of the vehicle and the ambient temperature. The conduction heat transfer from inner wall to fin surface is given as[1]:

$$q = k\,(T_w - T_{fin}) \qquad (1)$$

The convection heat transfer from fin surface to atmosphere air by free and forced air is given as[1]:

$$q = h_f\,(T_{fin} - T_{air}) \qquad (2)$$

This heat transfer from the fin is influenced by many fixed and variable constraints such as fin array, fluid flow velocity, fin geometry; shape and material etc. Many experimental methods are available in literature to analyze the effect of these factors on the heat transfer rate. Thornhill and May presented results for an experimental investigation in the cooling of finned metal cylinders[2,3]. The effect of cooling of internal combustion engine cylinder in free air is studied[4.]

The current paper represents an attempt to stimulate the parametric study of fin heat transfer on the air cooled engine using CFD codes. The experimental equation of the fin surface heat transfer coefficient using an aluminum cylinder at the air velocity from 7.2 to 72 km/h was derived out and found to vary for different array[5]. In another experimental study, the effect of varying the fin slit widths and slit setting positions, was tested and the temperature inside the cylinder is measured to determine the heat release from the cylinder[6]. The cooling of motor cycle engines using extended fins were carried out experinetally[7,8].

Two and three-dimensional decoupled and conjugate heat transfer analysis has been done with commercially available computational fluid dynamics (CFD) codes[9]. Problems of fluid and heat flow are governed by governing equations in the form of partial differential equations. In the present study, the numerical results obtained by ANSYS FLUENT 12.1 CFD code is validated by the experiments performed on internal combustion engine cylinder using aluminum fin in the thermal laboratory using thermocouples fitted on the surface of the fins.

In order to enhance the cooling of cylinder a parametric study is carried out by varying the fin material with different thermal conductivity values. Solutions have been obtained for different materials like aluminum, cast iron and copper. The heat transfer predominantly varies with air speeds and fin separation[2]. The fin spacing also influences the body mass and thermal limits of a fin array[9]. A study has been done for different fin spacing by keeping the wall height same and changing the number of fins. An analysis for pitch 7mm, 10mm and 14mm has been carried. The flow around the fin profile has been solved at different air flow velocities from 20 m/s to 80 m/s. The effect of turbo-charging[10] is also to be considered for complete analyses and the relationship between the thermodynamic properties[11] should be established. The study of trends observed for temperature measurements and heat transfer coefficient have been included in this paper. The analysis has been carried out in four stages.

Material and Methods

Experimental Set up and Measurement Techniques: The experimental setup has been shown in figure 1. Figure 2 shows the experimental cylinder along with thermocouple position in the cylinder and in the fin surface. The cylinder was made up of cast iron and has a fitted cap. The volume of the hollow portion of the experimental cylinder is 300 cm^3. Fin was made of an aluminum alloy (JIS A6010). The fins were fitted tightly in the cylinder. Heat storage liquid (SAE 40 oil) of 300 cm^3 was used to fill the cylinder in order to maintain uniform temperature in the cylinder. An induction heater with electrical power of 400 W was used to heat the oil to 150°C. J type thermocouples were inserted into the cylinder and fin to measure the temperature. The heat storage liquid was heated and is poured into the cylinder and the cap is placed above the cylinder. The temperature of the heat storage liquid was decreased by cooling at room temperature. The heat release from the cylinder was obtained by multiplying the heat capacity of the heat storage liquid by the difference between 150°C and the temperature after every 10 seconds at zero air velocity. The experiments were carried out at an ambient temperature of 33°C.

Modeling and Grid Generation: The cylinder, fin, air domain and oil are modeled using ICEM-CFD. The dimensions of cylinder and fins are exactly the same as that of the experimental setup. The whole assembly is splitted into 3 domains: i. Solid domain: The solid domain consists of the fin and cylinder. ii. Fluid domain I (SAE-40 oil): SAE-40 oil is placed inside the cylinder as the heat source. iii. Fluid domain II (Air): The surrounding domain is kept as air domain as surrounding air exists.

The 3-D model geometry is imported in ICEM-CFD meshing software for mesh generation. The domains are defined here and are classified as above three domains. Fluid solid interfaces are given the title FLSO and SOSO is used for solid-solid interfaces. The interfaces between air domain, cylinder and SAE-40 oil are defined. Figure 3 shows the mesh of the fluid oil and the finned cylinder. The meshing of rectangular air domain is done after inserting the geometry files of cylinder and fins to avoid mesh inside these regions.

Solver Setup in ANSYS fluent: The flow around the finned cylinder has been solved at zero wind velocity. The mesh interfaces has been created in ANSYS fluent. The temperature of the entering air was chosen to be 303 K. Outlet phase was given fixed pressure conditions of 101.325 kPa representing atmospheric pressure. All the other faces of the air domain are given the wall boundary conditions. The solver was selected as transient with gravity of 9.8m/s^2 to consider buoyancy effects due to natural convection. Solution initialization was done at 303 K for all zones. Oil domain was patched to a temperature of 423 K.

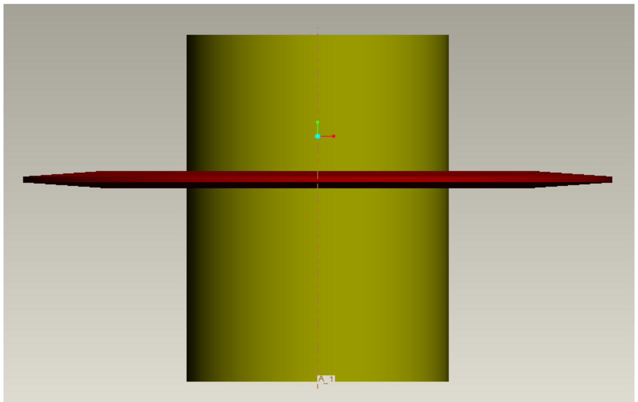

Figure-1
Experimental cylinder with fins

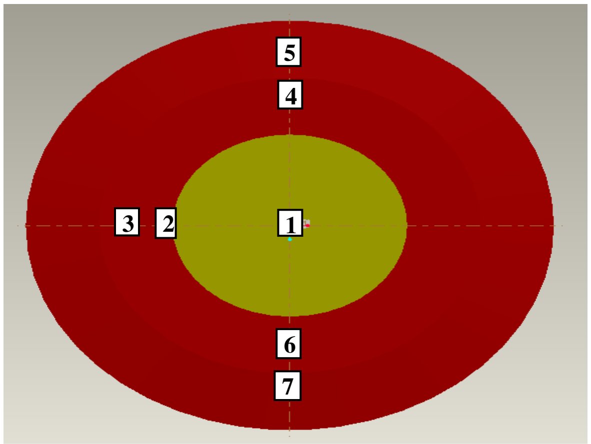

Figure-2
Placement of thermocouple on the fins and cylinder

Validation Results: It is observed from the CFD result that it takes 150 seconds for the oil domain to reach the temperature 339 K from 423 K. The temperature of air, cylinder and fins which are at ambient temperature is also increased by 26 K which confirms the heat transfer physics.

The experimental results show that the value of heat release by the oil through cylinder and fin is about 23.8 W. The heat release from the cylinder was obtained by multiplying the heat capacity of the heat storage liquid by the formula:

Heat release, $Q = mc_p\nabla T$

Where, m = mass of the heat storage liquid, in Kg, c_p= specific heat capacity of SAE-40 oil, in J/kg/K, ∇T= change in temperature after 10 seconds, in K.

Thus the numerical result by CFD analysis is calculated and the temperature of the fin for the first 100 seconds is plotted along with the experimental readings. Figure 4 shows the temperature at fin surface of numerical and experimental analysis, which is measured at a distance of 25 mm from cylinder surface. Figure 5 shows the plot of heat release from the oil which is calculated after every 10 seconds. From the plot it can be inferred that the experimental and numerical results show the same variation with deviation being less than +4%.

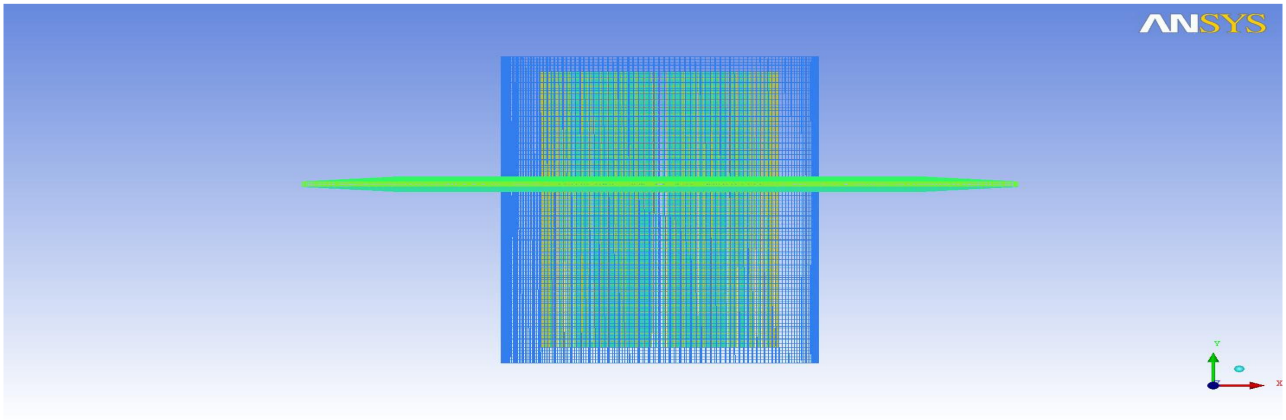

Figure-3
Meshed model of Cylinder, Oil domain and Fin

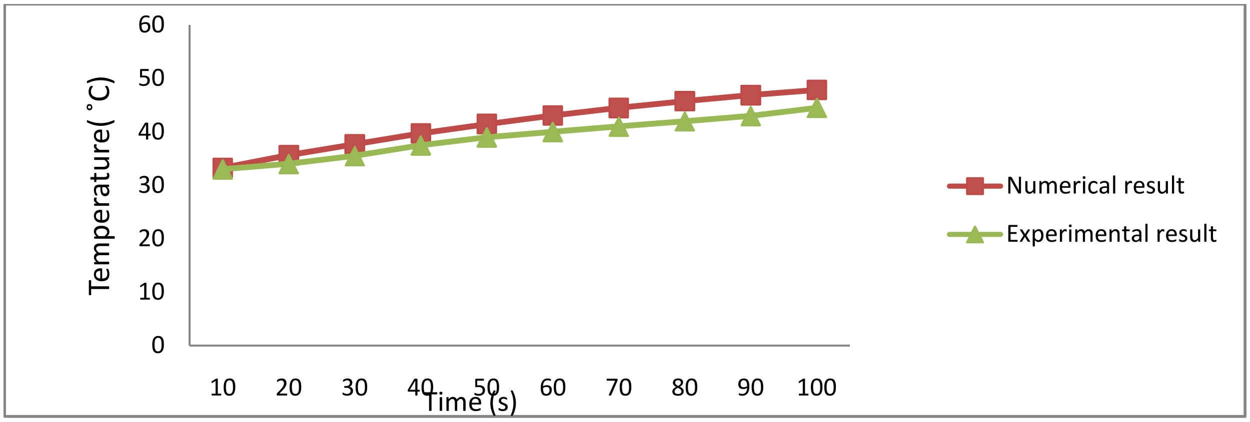

Figure-4
Time vs. Temperature plot for Numerical and Experimental Results

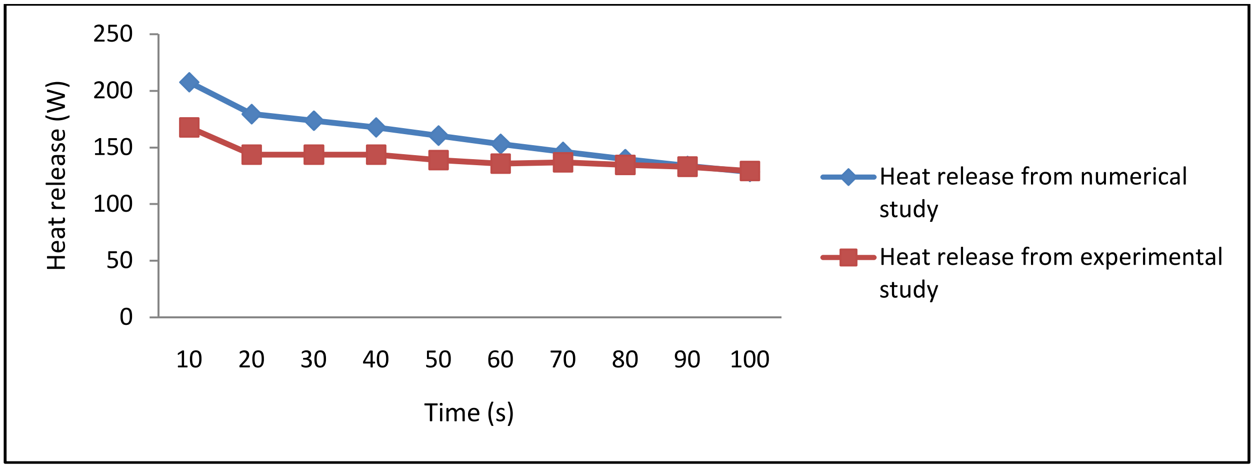

Figure-5
Heat Released vs. Time plot for Numerical & Experimental Study

Results and Discussion

Effect of Fin Material: To analyze the effect of material properties, copper, aluminum and cast iron were considered for the best heat dissipation considering both the conduction and convection heat transfer parameters. Three numerical models with different fin materials (copper, aluminum and cast iron) and same cylinder material (cast iron) were simulated under same operating conditions i.e. constant temperature of cylinder inner wall at 150°C and wind velocity of 60 Km/hr. Figure 6 shows the temperature profile on the copper fin surface. The temperature contours for cast iron fin is shown in figure 7. As inferred from the figure the temperature is more distributed on the copper fin, showing greater area of heat transfer.

Figure 8 shows the variation of coefficient of heat transfer with change in fin material at fin tip. Under steady-state conditions, copper fin has the maximum surface heat transfer coefficient at fin tip. Aluminum fin is marginally below the copper fin in terms of surface heat transfer co-efficient and cast iron fin has the lowest value of co-efficient.

Effect of Fin Pitch: Three different fin pitches of 7 mm, 10 mm and 14 mm have been analyzed for internal combustion engine cylinder with 80 mm length. The pitches have been measured from fin surfaces. The number of fin varies with respect to the change in the fin pitch. The number of fins is 6 for a fin pitch of 7 mm and it is 5 for a fin pitch of 10 mm.

Figure 9 show the meshed model of 6 fins having a spacing of 7 mm. The different fin pitch models were simulated at four different air velocities (20, 40, 60 and 80 Kmph). Results have been shown in figure 10. Different fin pitches are compared on the basis of net heat dissipated at fin tip by all the fins in model. The surface heat transfer coefficient is multiplied by the area of one fin and number of fins in every fin geometry. The maximum value of heat transfer is obtained for pitch of 10 mm. Figure 11 shows the contour of heat transfer through 10 mm fin pitch geometry at a velocity of 60 kmph.

Effect of Velocity of Air: To examine whether the performance of different fin pitches varies with wind velocity, simulation are carried out for all the different pin pitches for different air velocity. Meshed model for air domain and fins were created and shown in figure 12. The numerical analysis is carried out for different velocities from 20 to 80 kmph. The velocity is given in positive x direction. Apart from inlet and pressure outlet all surfaces of air domain are specified as wall condition. Figure 13 shows the contour of heat transfer through 10 mm pitch geometry at a velocity of 20 kmph. The temperature contour of same geometry at 80 kmph is shown in figure 14. The thermal boundary layer can be easily observed between fins in the figures. The region between the fins is hotter for 20 kmph in comparison to 80 kmph, showing less heat transfer at lower wind velocity.

The heat transfer coefficient of different fin array is plotted against variable air velocity in figure 15. The results show that the performance of fin model increases with wind velocity but the gradient decreases as wind velocity increases from 60 to 80 kmh.

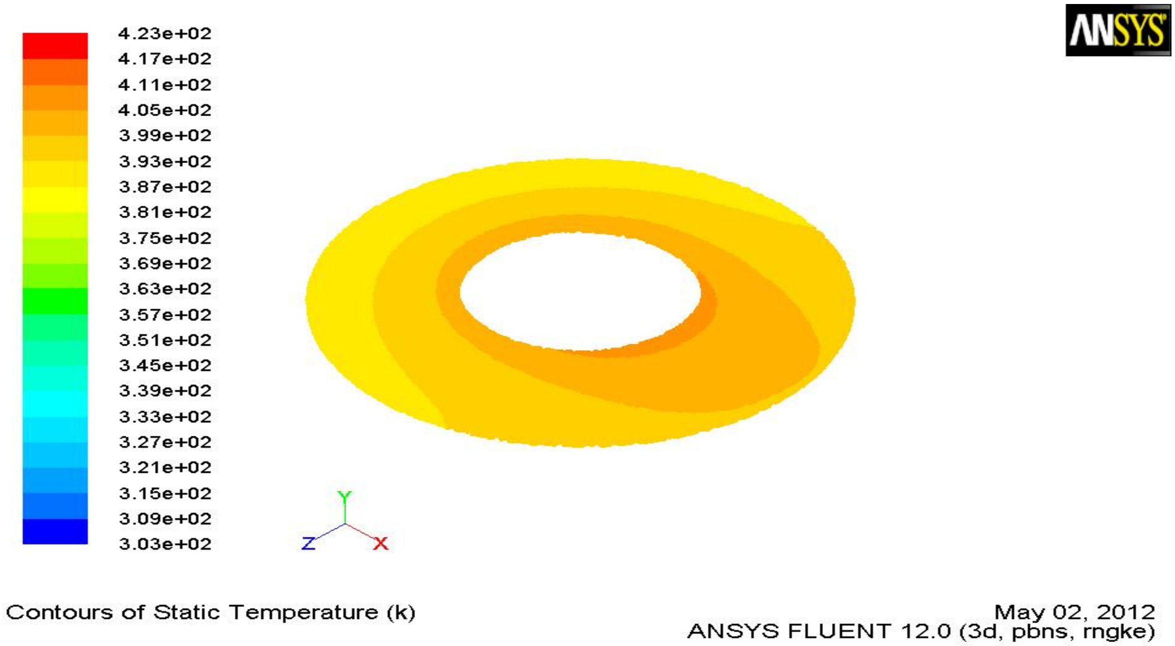

Figure-6
Temperature Contour plot of Copper fins

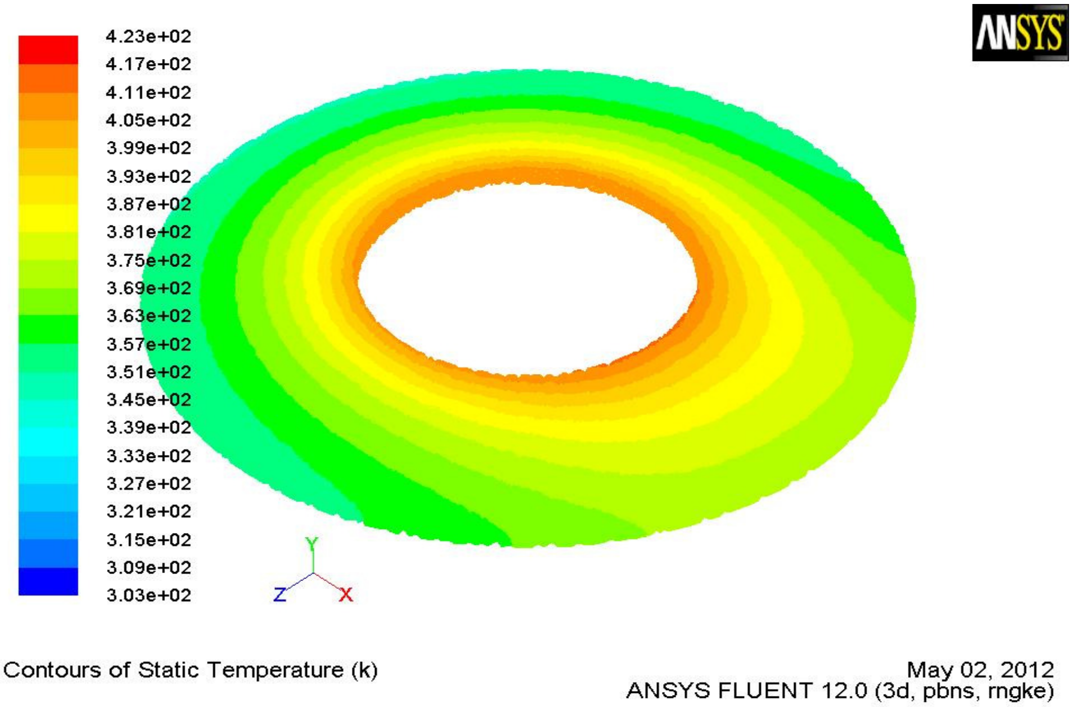

Figure-7
Temperature Contour plot of cast iron fins

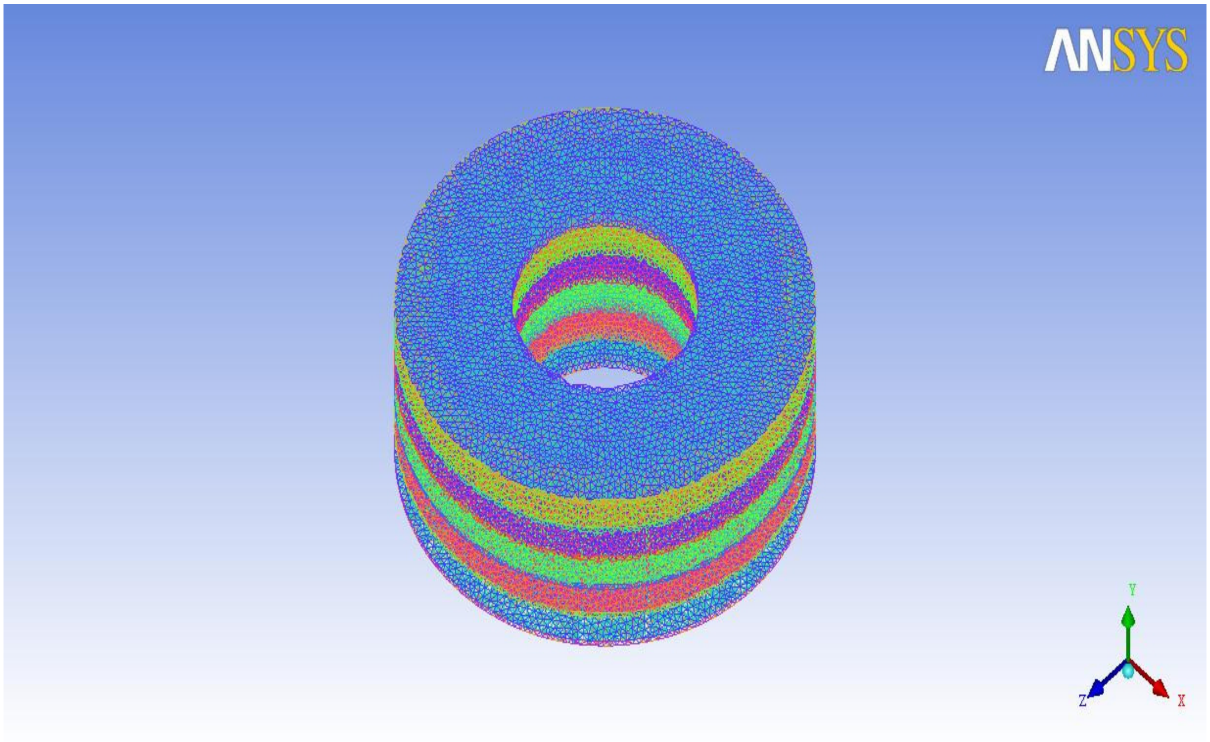

Figure-8
Meshed model of 6 fins with 7mm pitch

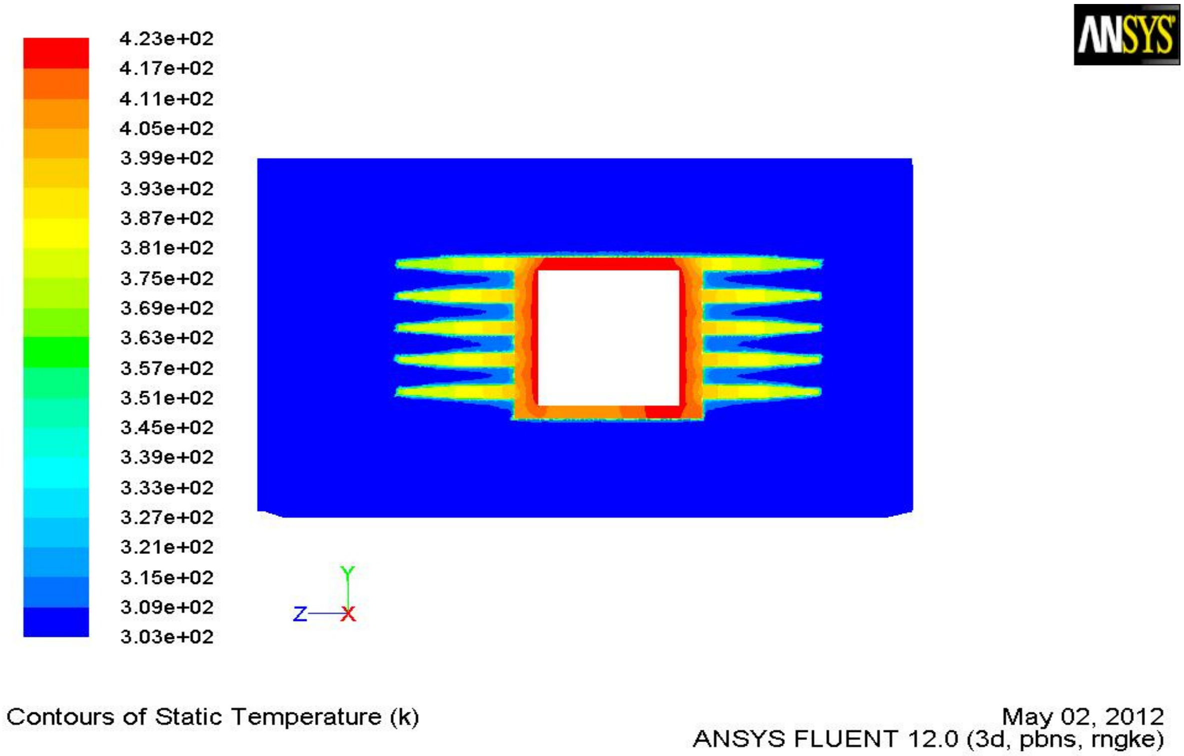

Figure-9
Boundary Layer plot of 5 fins with 10mm pitch at 60Kmph

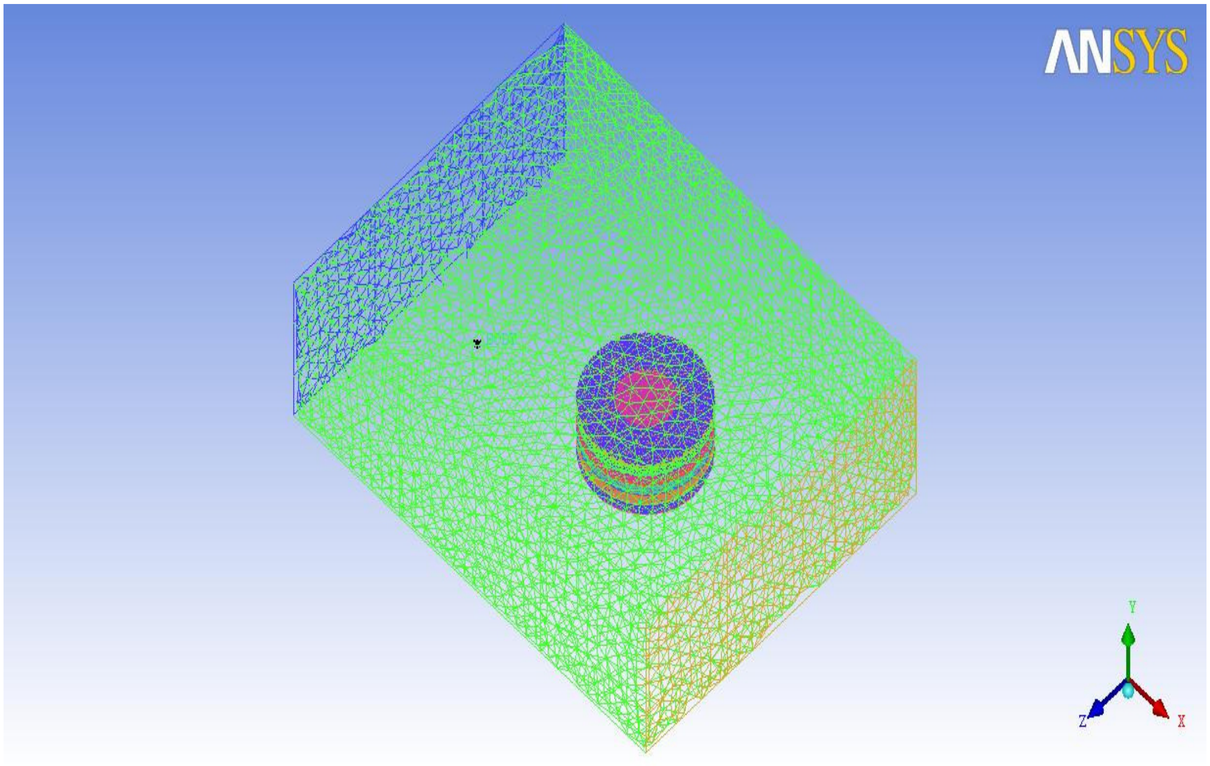

Figure-10
Meshed model with Air Domain, Cylinder & Fins

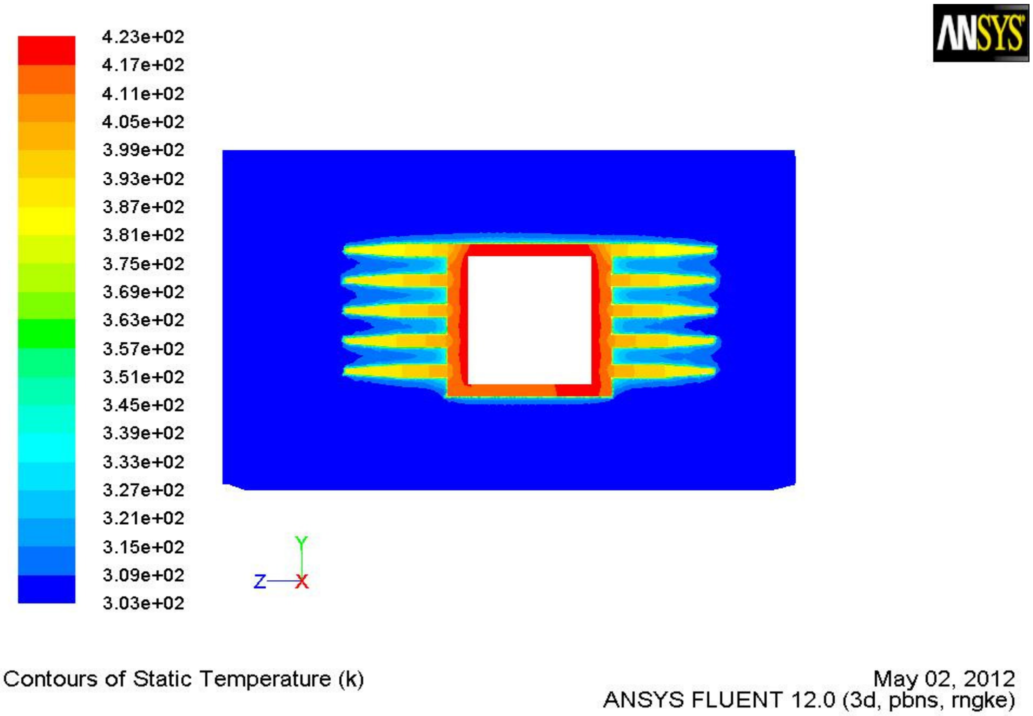

Figure-11
Boundary Layer plot of 5 fins at 10mm pitch at 20 Kmph

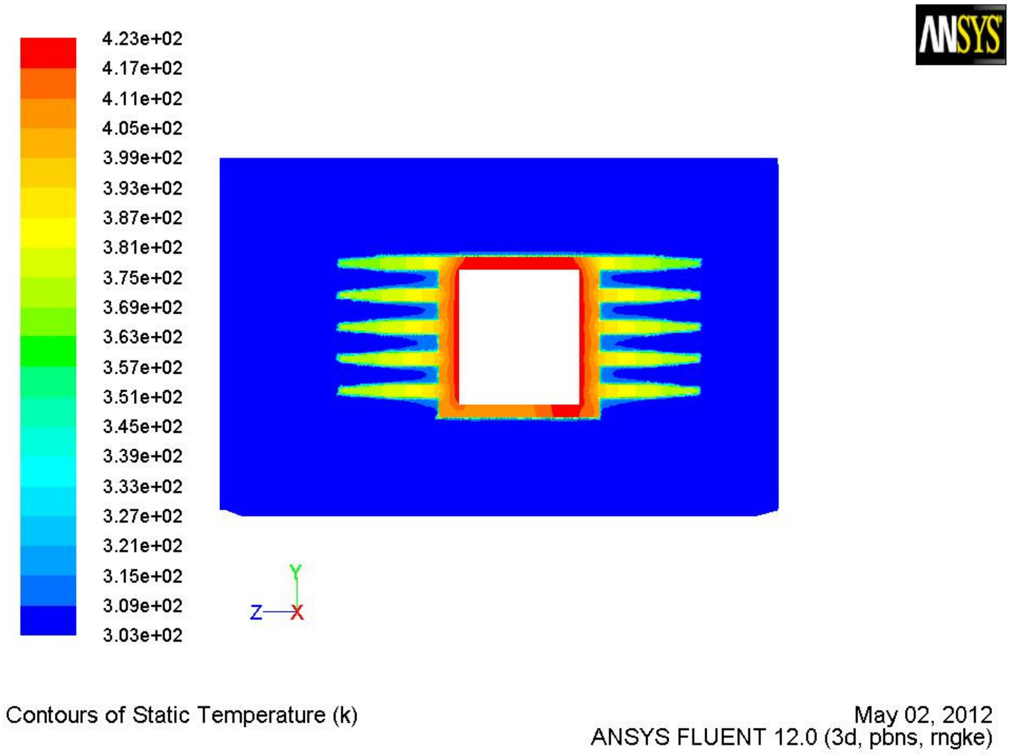

Figure-12
Boundary Layer plot of 5 fins at 10mm pitch at 80 Kmph

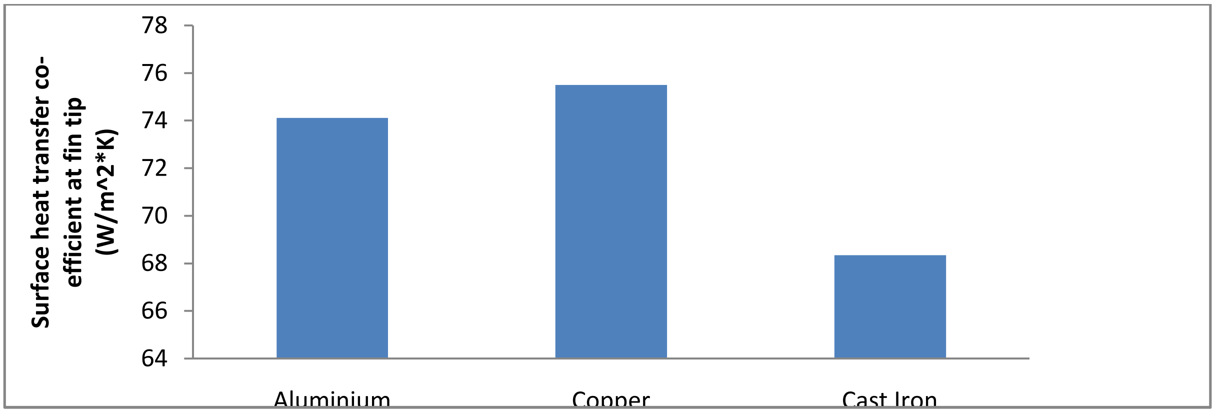

Figure-13
Plot of Heat Transfer for different materials

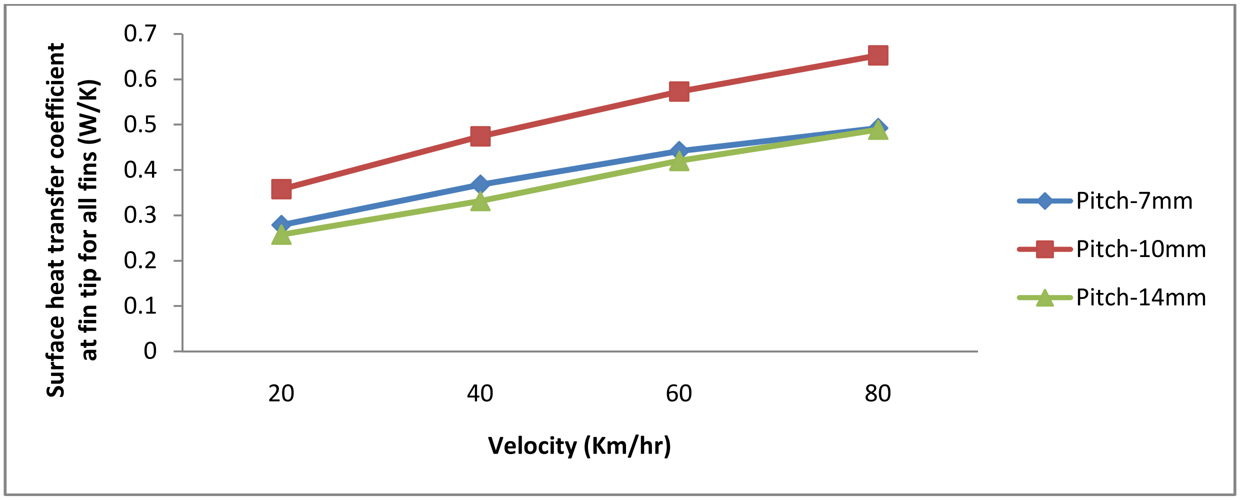

Figure-14
Plot of Heat dissipated at fin tip vs. Velocity for different fin pitches

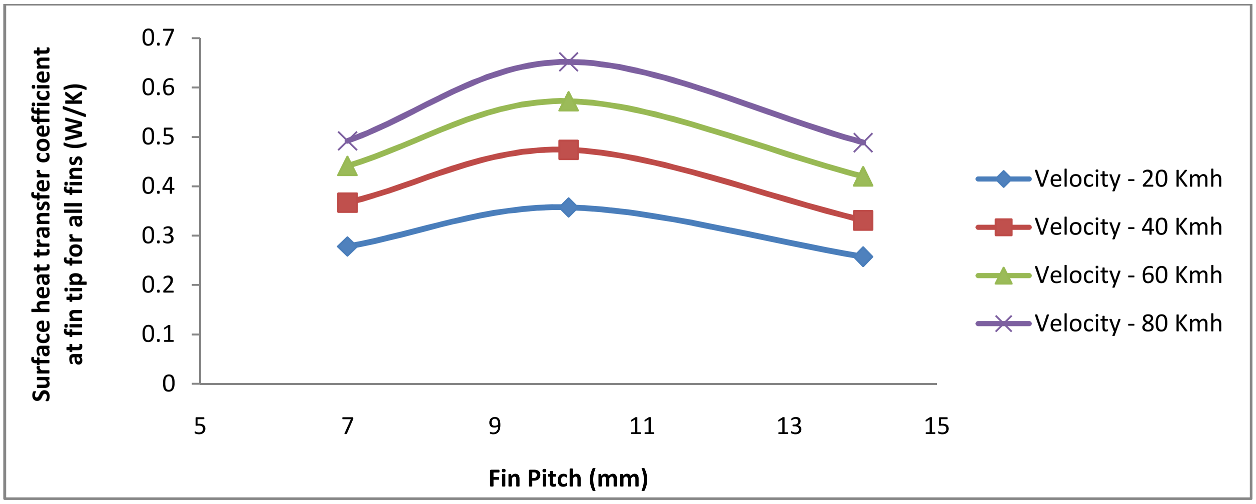

Figure-15
Heat dissipated by fins at tip at different velocities

Conclusion

For a given thermal load, the fin material and fin array parameters could be optimized in a better way by numerical simulation methods. CFD could be used to determine optimal values of fin parameters before actual design. To increase the cylinder cooling, the cylinder should have a greater number of fins. However, the cylinder cooling may decrease with an increased number of fins and too narrow a fin pitch. The is because the air could not flow well between the fins, thus the overlapping of thermal boundary layers occurs at the upper and lower fin surfaces.

The study reveals that the optimized fin material with the greatest effective cooling is copper, the effective heat transfer coefficient is found to be more for a pitch of 10mm and this optimized fin array parameters is helpful in improving the efficiency of the engine.

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